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HEMP Test on FD-565

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13. ABSTRACT *(Maximum 200 words)*

This report describes the test on the FD-565 Optical Fiber Digital Transmission System against the high-altitude electromagnetic pulse (HEMP). The background of this test is explained with the test objectives. The general FD-565 system configuration is described along with the test configurations. Also introduced are the test facility and data acquisition and processing system. Three different kinds of data are presented: operational data, bulk current data, and field level data. For the purpose of statistical analysis, the operational data are tabulated at the end of this report.

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Foreword

This document has been published as a Technical Information Bulletin by the Office of the Manager, National Communications System (NCS TIB 91-1, May 1991). It is published as a Harry Diamond Laboratories document so that it may be more widely disseminated.

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1. Introduction

The Harry Diamond Laboratories has performed tests on the FD-565 optical transmission system, an important telecommunications asset of the U.S. Public Switched Network (PSN), to determine its ability to survive the effects of a high-altitude electromagnetic pulse (HEMP). This test is part of the EMP Mitigation Program of the Office of the Manager, National Communications System (OMNCS), whose aim is to ensure that EMP would not significantly impede the reestablishment of telecommunications following an attack against the United States that includes high-altitude nuclear detonations. This report describes the FD-565 test object, the test facilities of the Patuxent River Naval Air Test Center, the data collected, and the test results.

1.1 EMP Mitigation Program

In response to Executive Order (EO) 12472 and National Security Decision Directive (NSDD) 97, the OMNCS sponsors the EMP Mitigation Program. The methodology for developing an EMP Mitigation Program plan is described in the OMNCS report, *EMP Mitigation Program Approach,* of September 1987. In that document, essential program steps are defined as identification of PSN assets critical for reconstitution, estimation of the EMP effects on these assets and the networks in which they are embedded, assessment of the impact of available EMP mitigation alternatives, and development of a comprehensive plan for implementing mitigation alternatives.

To attain the goals of the OMNCS, the EMP Mitigation Program attempts to maximize the value of the HEMP response data available. The program is not meant to be a survivability assessment program in the traditional sense. To understand the limitations, it is important to understand the constraints facing the program. To begin with, there are a large number of assets in the PSN. Although many of these assets may be of the same type, they can be implemented in various different configurations. In addition, the OMNCS is not empowered to force a standard configuration for each type of asset. Given these constraints, the OMNCS must attempt to priority rank the tasks and to obtain a general, network-level understanding of the HEMP response of the assets. The type of testing recommended will obtain data that are not applicable to any particular asset, but are representative of assets in the telecommunications networks of interest to the OMNCS. The data collected can then be used to describe these assets statistically. In this manner, the OMNCS can maximize the value of the information that is collected.

1.2 FD-565 Optical Transmission System

The OMNCS EMP Mitigation Program identifies critical telecommunication assets. The FD-565 transmission system, manufactured by Northern Telecom, Inc. (NTI), is such an asset. It is a high-capacity, single-mode, optical fiber digital transmission system that is used extensively in the PSN. The test of the FD-565 complements the evaluation and modelling of other telecommunication equipment (such as AT&T 4ESS and 5ESS switching systems, T1 and FT3C transmission systems, and NTI DMS-100 electronic switches).

The OMNCS asked the U.S. Army Harry Diamond Laboratories Nuclear Survivability Laboratory (HDL-NSL) to procure the test object, coordinate the activity, and conduct the test. The HDL-NSL has supported the NCS in similar activities for the past eight years. The HDL-NSL provided the HEMP expertise, capital equipment, and technical staff familiar with the HEMP phenomenon, its simulation, and its effect on command, control, and communications (C^3) systems. The HDL-NSL functioned as a technical consultant with supporting laboratory capability to the NCS.

2. Test Objectives

The objective of the test reported here was to expose the operational FD-565 to the HEMP environment of a simulator at levels from 10 to 60 kV/m and to determine the effects on the system at each level. The system behavior was categorized according to the following responses:

a. system or component damage requiring repair or replacement;

b. permanent upset requiring manual intervention for recovery;

c. transient upset with automatic recovery;

d. no effects.

A Tau-Tron S5250 digital signal generator and detector provided a DS-3 pseudorandom bit sequence to the terminal (DS-3 refers to digital signals operating at standard bit rates of 44.736 Mb/s). This sequence was multiplexed and converted to light at 570 Mb/s, transmitted through a 1-km single-mode fiber loop to the optical receiver, down-converted to an electrical DS-3 signal, and returned to the Tau-Tron detector. Data bit errors, bit error rate, and loss of synchronization or framing pulses were monitored by the S5250 and displayed. The operational data collected were used in the OMNCS network connectivity models. Consequently, for statistical purposes, at least 200 pulses were required.

3. Test Object Description

The FD-565 is a high-capacity optical fiber digital transmission system made by NTI, and operates at a 570.48-Mb/s line rate. Optional low-speed and high-speed protection switching is provided. The system combines up to 12 DS-3 (44.7-Mb/s) signals, which means 8064 noncompressed voice channels of 64 kb/s each, and overhead information in a single stream of light pulses for transmission over a single-mode optical fiber cable at 1310 nm. The FD-565 meets all network considerations for use in either long-haul interexchange applications or in point-to-point local operating company applications. This system is compatible with all equipment interfacing at the DSX-3 cross-connect point (that is, a digital signal cross-connect with predefined signal characteristics for DS-3 inputs and outputs).

The FD-565 consists of standalone signal-processing shelves that can be at terminal and intermediate sites (repeaters and drop-and-insert (D/I) sites). These sites, interconnected by optical fiber cables, contain the transmit and receive equipment. The signal-processing shelves can be mounted on any 584-mm (23-in.) mounting bay frame. The FD-565 system is supplied in a standard 2.13-m (7-ft) bay configuration.

The maximum recommended system length for digital long haul toll transmission is 6440 km (4025 miles). The system is divided into switching sections, each consisting of terminal and intermediate sites. The maximum recommended length for each switching section is 1200 km (746 miles); thus there is a maximum of 32 sites per switching section, or 37.5 km between repeater sites.

The FD-565 bay was installed on a 4 by 6 ft wheeled platform for ease in positioning the test object. The power supply included in the frame consists of a rectifier and 48-V gel-cel batteries. The rectifier was powered by 120 V.

3.1 System Diagnostics

The FD-565 incorporates a number of local and remote alarms that are structured so that the source of a problem can be found as effectively as possible. There are four levels of local alarms: the bay major and minor alarms, the shelf major and minor alarms, the maintenance control unit (MCU) faceplate alarm and status LED's (light-emitting diodes), and the circuit pack alarm and status LED's. All alarm, control, and status points can be viewed remotely via the peripheral interface options available for the FD-565, such as a CRT terminal, a maintenance display unit (MDU), E2A serial telemetry, and parallel relay interfaces. For example, when a CRT terminal is used, the FD-565 surveillance system can be fully accessed. This provides detailed

global system information to every level; the alarm status of each signal-processing shelf for up to 14 sites can be displayed. Selection of a specific signal-processing shelf provides the user level; individual alarm status and control points may be examined for each circuit pack.

3.2 Configurations

The FD-565 test object is a single-shelf, 1 to 1 protected system that carries one protection and one working channel at the high-speed level and 1 to 1 protection at the low-speed DS-3 level. It could be configured with up to 12 DS-3 inputs for 1 to 12 low-speed protection. Figure 1 represents a terminal-to-terminal application of the FD-565 terminal. The DS-3 signals and the optical signals shown are each bidirectional paths, where 1 to 12 are the 12 DS-3 signal positions. Optical channels P (protection) and 1 are the optical protection and working channels.

Figure 2 shows the test object configuration. For this test, a 500-m length of single-mode fiber was used in a loopback arrangement. The fibers connected to transmitter number 1 and receiver number 1 (the working channel) were spliced together at the far end of the 500-m cable. Also, the fibers connected to transmitter number 2 and receiver number 2 (the protection, or hot standby, channel) were spliced together at the far end of the 500-m cable. This resulted in a 1-km optical path between transmitter and receiver.

Figure 3 shows the terminal shelf equipped with the circuit cards required for the test object of figure 2. The circuit cards that the test object was equipped with are described as follows.

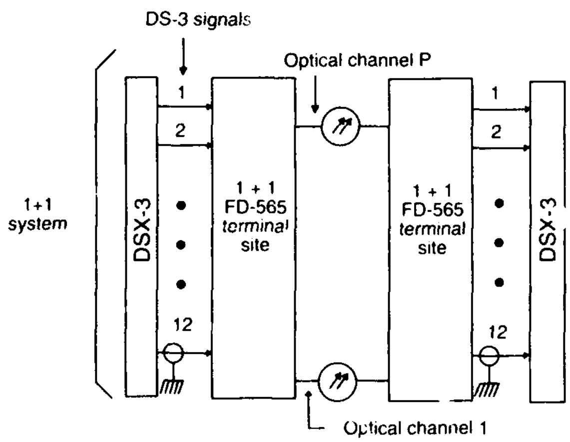


Figure 1. Terminal-to-terminal configuration.

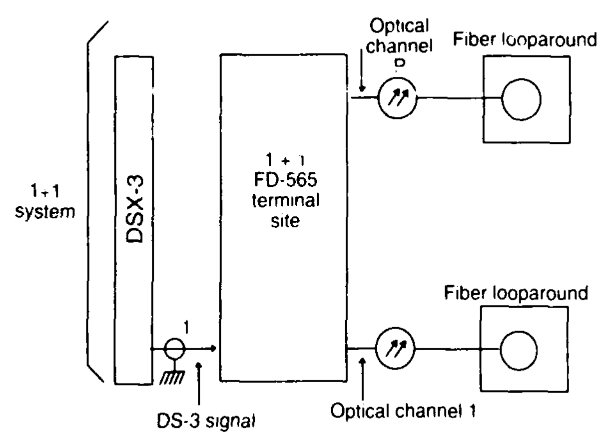
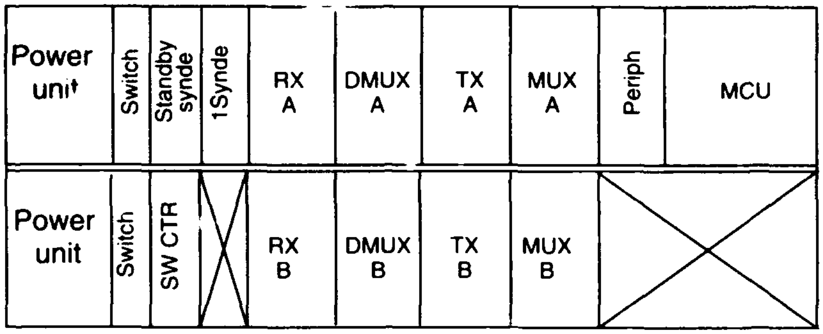


Figure 2. Test object configuration.

Figure 3. Terminal shelf configuration.



Power unit (power-supply unit). The −48-V power unit converts the −48 Vdc to the voltage required by the circuit cards on the shelf. The input voltage tolerance is from −37 to −60 Vdc. Each unit is protected against current surges by means of a precharge circuit that is operated by the on/off power switch. These two power-supply units share the load within 40- to 60-percent limits. Supply transfer is initiated by an over/under voltage condition on any of the outputs; the other unit then handles the full load.

Switch (switch unit). The switch unit is composed of a transmit section and a receive section. The transmit section of the switch unit splits the incoming DS-3's into two paths: one path is directly routed to the working synde (synchronizer/desynchronizer), and the other is routed to the standby synde by means of the bridge relay. The receive section of the switch unit contains 24 make-or-break contacts, four for each DS-3. Under normal operating conditions, two contacts block the path of the DS-3 from the standby synde to the cross-connect. A third contact allows the DS-3 to pass to the cross-connect from its working synde. The last contact ensures that the bridged DS-3 is terminated by a 75-Ω load when no switch is in effect.

SW CTR (switch control unit). The switch control unit interfaces between the maintenance bus and the switch unit(s). The SW CTR latches and decodes the switch/bridge commands from the maintenance bus, provides relay drivers to the switch units, and monitors switch operations. Unit alarm status for the SW CTR and the status of the switch units are sent out to the MCU by way of the maintenance bus.

Standby synde. The standby synde unit is available as a backup for the first (primary) synde unit.

1Synde (first synde unit). In the transmit direction, the synde unit accepts the incoming DS-3 signal from a switch unit, regenerates it, decodes it from a B3ZS (bipolar three-zero substitute) signal to a unipolar signal, synchronizes it (using a 46-MHz gapped clock signal provided by the multiplexer unit), and finally sends it to both multi-

plexer units. In the receive direction, the DS-3 data (coming from the demultiplexer) are desynchronized from 46 Mb/s to the original bit rate, and are then encoded from a unipolar to a B3ZS signal. Both the 46-Mb/s data and gapped clock signal are supplied by the demultiplexer unit. The synde unit monitors the DS-3 signal for the frame loss condition that occurs when a DS-3 frame alignment cannot be established. The delayed output of the elastic store is compared with the decoded synde output, and an alarm is raised if a discrepancy is found. The frame loss alarm and the comparator alarm are combined (ORed) to yield a receive alarm (that is, a receive alarm will be raised if any of the previously mentioned alarms are active). The synde unit can also perform parity-bit correction, as well as FT-3 blue-signal insertion (at the receive end). (A blue signal is a 1010 signal every 84 bits followed by one frame bit.) The default is for a blue signal to be inserted on loss of DS-3, and no parity-bit correction; these features can be enabled or disabled by means of a CRT terminal.

RX A/B (receiver unit A/receiver unit B). The receiver unit accepts a 570.480-Mb/s optical signal, which it amplifies and equalizes. The clock signal is extracted (using a phase-locked loop), and the data are recovered. Both clock signal and data are output by means of coaxial connectors.

DMUX A/B (demultiplexer unit A/demultiplexer unit B). The demultiplexer unit accepts the 570.480-Mb/s data stream as well as the 570.480-MHz clock signal from the receiver unit by way of two 50-Ω coaxial cables. It finds the framing bits, extracts the overhead information, and descrambles and demultiplexes the data. The resulting 12 46-Mb/s signals are then sent to their respective synde units. The demultiplexer unit also decodes the stuff bits and provides the appropriate gapped clock signal to each synde unit.

TX A/B (transmitter unit A/transmitter unit B). The transmitter unit accepts a 570.480-MHz clock and data signal, retimes the data, and generates an equivalent optical data waveform. Both clock and data signals are input, by means of coaxial connectors, at the front of the unit.

MUX A/B (multiplexer unit A/multiplexer unit B). The multiplexer unit accepts a 46-Mb/s data stream from each synde unit (including the standby unit). A stuff request signal is also received from each synde unit; this signal serves to appropriately gap the 46-MHz clock signals that are sent by the multiplexer unit to each synde unit independently. The 12 46-MHz data streams are then interleaved, and the resulting signal is scrambled with a specific scrambling sequence. The overhead data are then inserted, and the resulting

570.480-Mb/s signal, along with a 570.480-Mb/s clock signal, is sent to the transmitter unit by means of two 50-Ω coaxial cables. The 570.480-MHz master clock generator on multiplexer A is aligned with the clock generator on multiplexer B, which becomes the master generator in the event of a failure on multiplexer A.

Periph (terminal interface unit). The terminal interface unit, which is one of the peripheral interface units, provides a buffered interface between the MCU and the MDU, a CRT terminal, or an RS-232 modem. The unit contains an RS-232 port (25-pin D-subminiature connector) through which serial information is sent and received, using an RS-232 interface.

MCU (maintenance control unit). The MCU incorporates the intelligence of the FD-565 system. It is equipped with processors for system communication, alarm and control function, and system interface. The system software resides on the MCU. The functions provided by the MCU fall into two basic categories: primary and optional.

The primary functions are

- operation of maintenance bus,
- automatic protection of the high-speed and low-speed traffic,
- display of status and alarms on the faceplate,
- system monitoring,
- activation of minor and major shelf and bay alarms,
- accepting limited commands from faceplate, and
- providing intersite communication for alarm reporting.

The optional function is providing access to alarms and performance data through external interfaces (serial and/or parallel).

4. Test Object Data Collection

During the test, three kinds of data were collected: operational data, bulk current data, and field level data. The data and the methods of data collection are described here. The data are presented in section 7.

4.1 Operational Data

The test requirements called for the FD-565 system to be in an operational mode. The Tau-Tron S5250 (fig. 4) sends a DS-3 data-rate signal (44.736 Mb/s) to the FD-565 and receives the returned DS-3 data-rate signal from the FD-565. The test set compares the transmitted and received signals and measures the performance according to the parameters selected.

The S5250 transmitter section was set up to provide a bipolar output at 44.736 Mb/s (the DSX level) with a B3ZS code. This output is a 0.91-V peak level passed through a cable simulator equivalent to 450 ft of 75-Ω cable. The data pattern was a pseudorandom bit sequence (PRBS) of $2^{15} - 1 = 32{,}767$ bits, with DS-3 framing bits and no errors injected into the data stream.

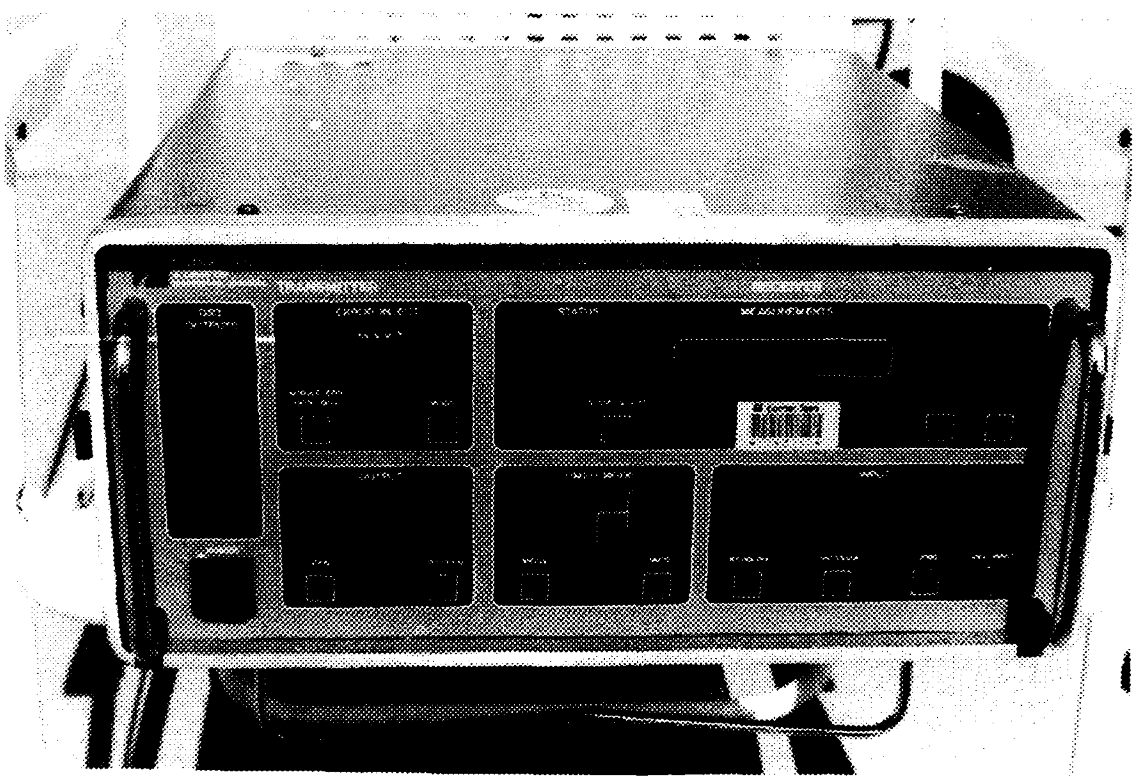


Figure 4. Tau-Tron S5250.

The receiver was set up to receive the transmitted signal at a level of +6 dB to below –26 dB about the nominal DSX level. In addition, the receiver would automatically recognize the blue signal (alternating 1's and 0's) even while monitoring the PRBS signal.

The S5250 was installed in a shielded box with filters on the ac power line to prevent the simulated HEMP fields from disturbing the test set. The connections between the DS-3 test set and the DS-3 transmit and receive connectors in the FD-565 terminal shelf were made with 75-Ω RG59 coaxial cable 15 ft long.

The S5250 was set up to measure data bit errors in a single timed mode; i.e., the test set was programmed to measure data bit errors over a single five-minute interval. Generally, the test was started at about the time the simulator began charging, and the test was manually stopped after the simulator was fired. The interval between these events was as short as 45 s and as long as 4 min, depending on how soon before the pulse the test was started.

The receiver displayed the following data on the 7-character LED display, one category at a time, under the control of pushbutton switches:

a. **total errors**: This value is the number of errors detected during the timed interval.

b. **bit error rate**: The bit error rate calculation is continuously made every 10^8 bits—this measurement could not be recorded because the test set was in a closed shielded box during the pulse, and by the time the door was open, the error rate in the 10^8 bit interval was zero.

c. **average error rate**: The average bit error rate is calculated over the timed interval of the test. As the timed interval increased after the pulse and the errors caused by the pulse, the average error rate was reduced.

d. **error seconds**: This value is the number of second-long periods in which errors occurred—during this test the number was always one.

e. **percent error-free seconds**: This value is calculated from the number of error-free seconds in the test divided by the total number of seconds in the test as a percentage; a running total is kept. As the test interval increases, this number increases.

f. **elapsed time**: This is the total time of the test. The test set was configured for a five-minute timed interval, with manual start and auto stop after five minutes. The timing was manually stopped after the pulse when the door to the shielded box was opened.

Two columns of status indicators are on the front panel of the S5250. The left column is the input signal status (NO-SIG, NO-FRAM, NO-SYNC, BLUE) and the right column is the test status (IN PROCESS, STOP, OVERFLO). These are described as follows:

a. **NO-SIG**: This indicator lights when the DS-3 signal is lost. If no bipolar pulses are detected for 44 $\mu s \pm 20$ percent, the NO-SIG indicator lights continuously, indicating a current signal loss. If bipolar pulses are then detected (signal regained) during the test interval, the NO-SIG indicator will flash, indicating a history of signal loss and that currently a signal is detected.

b. **NO-FRAM**: This indicator lights continuously while a "no-frame" condition is true (that is, when no signal is sent to the receiver or no DS-3 frame information is present at the receiver input). The indicator flashes when the condition is not true, that is, if there is a history of no-frame conditions during the test. The indicator is forced to off (does not light) if the S5250 is in the unframed mode.

c. **NO-SYNC**: The indicator lights when signal synchronization is lost. A signal is considered in synchronization if less than 40 bit errors occur over a period of 100 clock cycles. When 40 or more bit errors occur in 100 clock cycles for 8 successive tries, the signal will be considered out of synchronization and the NO-SYNC indicator will light continuously. If signal synchronization is regained, the NO-SYNC indicator will flash; this indicates a history of synchronization loss during the current test time interval.

d. **BLUE**: The indicator lights continuously while a blue signal is detected. It flashes if a blue signal has been detected at some point during the test. It is forced to off (the indicator does not light) if the S5250 is in the unframed mode.

e. **IN PROCESS**: The indicator lights if a test is in progress.

f. **STOP**: The indicator flashes to show that a test is not currently being made.

g. **OVERFLO**: The indicator flashes when a measurement has overflowed the 7-digit display.

4.2 Bulk Current Data

Bulk current measurements for each configuration were made on the ac input power cable, the ground cable, the DS-3 input/output cable pair, and the steel-jacketed optical fiber cable in configuration 4 only. The data were collected by the Data Acquisition and Processing System (DAPS), which collects data from the bulk current probes via a fiber-optic link and stores the data for future processing.

The test points for the bulk current data are identified as follows:

F00001	ground cable
F00002	ac power cable
F00003	optical fiber cable, steel shield (configuration 4 only)
F00005	DS-3 in/out

4.3 Field Data

Electric field measurements were made on the last day of the test at the three locations of the terminal. Both vertical and horizontal E-fields were measured. The fields were measured with an E-field sensor, and the data were collected and processed by DAPS as with the bulk current measurements.

5. Test Facilities

Because of the Army's decision to cease radiated pulse testing at the HDL Woodbridge Research Facility (WRF) and relocate the HDL simulators elsewhere, the Navy's TACAMO EMP simulator was used for the program. This simulator is at the Patuxent River Naval Air Test Center in Lexington Park, MD, approximately 100 miles from the HDL WRF.

5.1 Pulser/Antenna Control

The TACAMO EMP simulator (TES) was used as a source to simulate the EMP environment. The TES is a horizontally polarized dipole (HPD) free-field pulse (FFP) source facility capable of simulating a high-altitude EMP environment, having a field strength of 50 kV/m at 25 m from the center of the pulser. The HPD EMP source generator is known as the ML-5 pulser. It is a 5.0-MV, dual Marx, single-switch-type machine designed and constructed by Maxwell Laboratories, Inc. The HPD is a combined biconic and cylindrical antenna, designed and constructed by EG&G Washington Analytical Services Center, Inc. It radiates the broadband frequency response of the generated EMP. The dielectric support structure suspends the antennas and the MS-5 generator above the test object. Together the components of TES provide a large (116-ft pad radius) spatially uniform, downward-propagating HEMP-illuminated test volume. The TES can provide higher levels of field strength if the pulser is lowered for the prime test object. This adjustment sacrifices the plane-wave character of the simulated field.

5.2 Data Acquisition and Processing Systems (DAPS)

The TES DAPS can make 3000 measurement attempts per day, resulting in a minimum of 750 successful test point measurements per day. The TES DAPS consists of two transportable, EMP-shielded modules, each 8 × 8 × 20 ft. One module contains two independent five-channel segments. The other contains a single five-channel segment and the test director; it is expandable for future addition of a second segment (but not a second test director).

Each five-channel segment is provided with its own Digital Equipment Corporation MicroVAX II minicomputer and CSPI Mini-Map array processor for controlling, acquiring, and processing data gathered on its own instrumentation subsystem. Each 5-channel instrumentation subsystem contains five independent channels of EG&G Optical Data System (ODS) wideband fiber-optic (FO) telemetry links, distribution amplifiers, high-speed LeCroy 6880 transient digitizers, and an automated probe connection verification system (PVS).

Each module also contains an industry standard nine-track magnetic tape deck for data archiving, a network analyzer for instrument calibrations, a high-speed oscilloscope for maintenance support, and a monitor and communication system providing both rf and FO communications.

The four group-leader (GL) terminals are FO linked to the modules. A probe setter with a portable FO communication set and bar-code reader is connected to each of the segments. Database and status information is shared between the segments via an FO-linked ethernet.

The TES DAPS software supports test planning in a relational database environment. Test-point connections are automatically verified for correct probe installation and instrumentation type. Data are automatically acquired, stored, and processed with frequency-domain instrumentation corrections. A Math Analyst Package (MAP) provides further processing capabilities to the TES DAPS software.

6. Test Configurations

Four configurations were used in the conduct of this test. Configurations 1 through 3 employed identical equipment, differing in the location of the test object on the pad with respect to the simulator. In configuration 4, the test object was modified by the substitution of a steel shielded optical fiber cable for the dielectric optical fiber cable.

In configurations 1 through 3, the equipment used consisted of the equipment frame containing the batteries, power supply, power distribution, and terminal shelf mounted on the wheeled platform, with the 500-m reel of dielectric optical fiber cable and the cable terminating shelf on the platform; the cable terminating shelf and terminal shelf were interconnected by means of optical fiber patch cords (fig. 5).

Figure 5. Test object FD-565.

In configuration 1, the test object was on the edge of the pad on the simulator centerline, 50 m from the pulser. In configuration 2, it was on the simulator centerline 20 m from the pulser. In configuration 3, it was on the simulator centerline 3 m from the pulser. This location was at the edge of the cradle that the pulser was lowered into at the end of each test day.

A 100-m-long ac power cable was connected to the ac power at the edge of the pad near the DAPS access road (approximately 20 m from the antenna) and routed so as to minimize coupling to the power cable. The frame was grounded in configuration 1 to a ground rod just off the pad, in configuration 2 to a ground terminal on the pad about 6 m away from the frame, and in configuration 3 to a ground terminal on the pad about 4 m away from the frame.

In configuration 4, the locations of the terminal equipment, the ac power, and frame grounding were the same as in configuration 3. In this configuration, the dielectric optical fiber cable was replaced with an outside plant cable having a corrugated steel shield around the inner fiber-carrying cable. This cable shield was grounded to the equipment frame, and the cable was unreeled on the ground for 50 m parallel to the simulator about 3 m away. The far end of the cable shield was ungrounded. The fibers were spliced to again give a 1-km fiber length between transmitter and receiver optics.

7. Test Results

7.1 Summary Results

Table 1 summarizes the measured data collected during this test for each configuration.

The first two rows of data are the peak measured values of the horizontal and vertical electrical fields at a point 1.5 m above the ground. This corresponds to a location at the height of the terminal shelf.

The bulk current measurements are given for the currents measured on the ground cable, the ac power cable, and the DS-3 test set input/output cables in all four configurations, as well as the bulk currents on the corrugated steel shield of the outside plant optical fiber cable used in configuration 4. Two measurements were made for each test point in each configuration.

Table 1. Measured data summary

Type of data	Configuration			
	1	2	3	4
Peak horizontal electric field, E_H (1.5 m above ground)	14.3 kV/m	27.3 kV/m	30 kV/m	30 kV/m
Peak vertical electric field, E_V (1.5 m above ground)	316 V/m	520 V/m	5.5 kV/m	5.5 kV/m
Bulk currents, I_{bulk}, on ground cable (F1)	29.1 A	73.5 A	81.3 A	126 A
I_{bulk} on ac power cable (F2)	23.3 A	57.3 A	88.7 A	132 A
I_{bulk} on optical fiber steel shield (F3)	NA	NA	NA	149 A
I_{bulk} on DS-3 I/O cables (F5)	20.1 A	26.4 A	53.6 A	97 A
Horizontal distance from pulser	50 m	20 m	3 m	3 m
Slant range to a point 1.5 m above ground	57.6 m	34.8 m	28.7 m	28.7 m
Elevation angle	29.7°	54.9°	84.0°	84.0°
Scaled horizontal field (from 50 kV/m at 25 m)	21.7 kV/m	35.9 kV/m	43.6 kV/m	43.6 kV/m

The scaled horizontal electric field is the $1/R$ value of the electric field at the slant range, based on a free-field value of 50 kV/m at 25 m from the pulser. The HPD simulator can achieve 50 kV/m on the ground under certain circumstances if the antenna is lowered or the charging voltage is raised. Neither option was achievable at this facility at the time of this test. Consequently, the high-level exposure to free-field levels of 50 to 60 kV/m must be obtained in a future test with other equipment. Scaling the horizontal electric field by $1/R$ to 60 kV/m gives a slant range of 21 m. Therefore the test object must be elevated by approximately 10 m to be exposed to the maximum level.

7.2 Operational Test Results

Table 2 gives the results of the operational testing. The shot number is assigned by the pulser control and is a cumulative record of numbers of pulses fired. All data taken are cross referenced to the pulse number.

The risetime and peak value are the parameters of the pulse, calculated from the B-dot value measured at the location of the reference field sensor.

The total errors are the bit errors detected by the Tau-Tron S5250 during the test interval. The average error rate is the bit error rate averaged over the test period—the S5250 calculates a bit error rate measurement every 10^8 bits, or approximately every 2.25 s. With the S5250 *in a shielded cabinet*, this measurement was not obtained, but can be calculated: for pulse number 14759, 9 measured bit errors in 10^8 bits gives a bit error rate of 9×10^{-8}.

The test interval is the time taken for the test. Although the S5250 was set up to generate a five-minute interval from a manual start, the S5250 was manually stopped following the pulse and the data recorded.

The percentage of error-free seconds during the timed period is also given. For this test, the number of error seconds was always equal to 1; therefore the percentage of error-free seconds is equal to the number of seconds in the timed interval minus 1 error second, divided by the total number of seconds in the timed interval. The period ranged from 50 s to 4 min 24 s, for an error-free second range of 98 to 99.62 percent.

The comments column contains a notation if the synchronization or framing was lost, or if a blue signal (loss of DS-3 input) was detected. In each case where the notation appears, the indicator lights were flashing, meaning that one of the conditions was detected at some point during the test interval, but was not then present.

Every pulse caused a number of bit errors to occur. Generally the errors were increased with increasing field level, but less than 100 errors were detected. At higher field levels more of the pulses caused loss of DS-3 signal, synchronization, or framing, with the number of errors detected on the order of 100,000. In every case, the terminal recovered to a zero bit error rate condition. The high-level and low-level protection switching—monitored by LED on the various circuit boards and the MCU—did not occur during any pulse.

Table 2. FD-565 fiber-optic system test results
(a) Configuration 1

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14759	7.5	14.5	9	1.5×10^{-9}	2:14	99.25	
14760	7.5	14.6	9	1.6×10^{-9}	2:06	99.21	
14761	7.1	16.4	4	9.0×10^{-10}	1:48	99.01	
14762	7.6	14.6	9	1.1×10^{-9}	2:01	99.11	
14763	7.3	14.8	12	1.9×10^{-9}	2:22	99.3	
14764	7.5	15.7	14	3.9×10^{-9}	1:21	98.77	
14765	7.6	15.2	16	4.4×10^{-9}	1:22	98.78	
14766	7.8	15.4	10	1.5×10^{-9}	2:34	99.25	
14767	7.6	15.1	6	6.0×10^{-10}	3:46	99.56	
14768	7.3	16.4	13	2.0×10^{-9}	2:28	99.32	
14769	7.5	16.5	13	5.1×10^{-9}	0:58	98.28	
14770	7.3	16.1	13	3.8×10^{-9}	1:18	98.11	
14771	7.6	15	7	1.9×10^{-9}	1:25	98.82	
14772	7.5	15.1	13	3.6×10^{-9}	1:22	98.18	
14773	7.6	15.6	8	2.3×10^{-9}	1:19	98.73	
14775	7.5	16.1	7	1.9×10^{-9}	1:22	98.18	
14776	7.3	17.4	129626	4.9×10^{-5}	1:00	98.33	NSyn, NF, B
14777	7.6	16.8	9	3.3×10^{-9}	1:01	98.36	
14778	7.3	16.4	17	4.8×10^{-9}	1:27	98.98	
14780	7.1	17.3	13	3.7×10^{-9}	1:20	98.15	
14781	7.5	17.2	13	3.2×10^{-9}	1:33	98.92	
14782	7.1	17.7	9	2.0×10^{-7}	1:33	98.92	
14783	7.4	15.9	7	1.7×10^{-9}	1:31	98.9	
14784	7.5	16.8	7	2.4×10^{-9}	1:05	98.46	
14785	7.3	17.7	10	2.9×10^{-9}	1:18	98.11	
14786	7.6	17	14	3.8×10^{-9}	1:23	98.79	
14787	7.5	17.2	11	2.1×10^{-9}	1:59	99.16	
14788	7.5	16.9	12	2.0×10^{-9}	2:17	99.27	
14789	7.5	17	11	1.6×10^{-9}	2:32	99.34	
14790	7.3	16.4	12	1.6×10^{-9}	2:49	99.4	

Table 2 (cont'd). FD-565 fiber-optic system test results
(b) Configuration 2

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14791	7.8	16.6	17	4.2×10^{-9}	1:32	98.91	
14792	6.6	17.7	20	5.2×10^{-9}	1:27	98.85	
14793	7.8	17.3	16	3.6×10^{-10}	1:49	99	
14794	7.8	17.5	16	4.5×10^{-9}	1:21	98.76	
14795	7.8	16.4	11	2.8×10^{-9}	1:28	98.86	
14796	7.5	17.3	15	3.6×10^{-9}	1:34	98.93	
14797	7.6	17.3	21	5.2×10^{-9}	1:32	98.91	
14798	7.5	17.8	13	3.0×10^{-9}	1:39	98.99	
14799	7.6	18.2	15	3.2×10^{-9}	1:46	99.06	
14800	7.8	17	12	2.1×10^{-9}	2:09	99.22	
14801	7.6	17.3	20	3.1×10^{-9}	2:25	99.31	
14802	7.5	17.9	19	4.1×10^{-9}	1:44	99.04	
14803	7.8	17.8	18	4.2×10^{-9}	1:36	98.96	

(c) Configuration 3

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14804	7.6	15.4	22	4.3×10^{-9}	1:55	99.13	
14805	7.6	16.1	120816	1.8×10^{-5}	2:30	99.33	NSyn, NF, B
14806	7.6	15.8	24	2.1×10^{-9}	4:20	99.61	
14807	7.3	17.4	30	6.8×10^{-9}	1:39	98.98	
14808	7.6	16.6	45	5.3×10^{-9}	3:13	99.48	
14809	7.6	15.2	120814	4.7×10^{-5}	0:58	98.28	NSyn, NF, B
14810	7.3	16	36	8.4×10^{-9}	1:37	98.97	
14811	7.5	17.7	99542	1.9×10^{-5}	2:01	99.11	NSyn, NF
14812	7.5	16.9	33	9.4×10^{-9}	1:19	98.73	
14813	7.6	17.9	35	7.8×10^{-9}	1:42	99.01	
14814	7.5	16.9	30	3.5×10^{-9}	3:13	99.48	
14815	7.8	14.8	43	8.3×10^{-9}	1:51	99.14	
14816	7.6	16	118615	1.6×10^{-5}	2:52	99.41	NSyn, NF, B
14817	7.6	16.8	37	5.4×10^{-9}	2:34	99.35	
14818	7.5	16.6	100700	2.8×10^{-5}	1:22	98.[illegible]	NSyn, NF
14819	7.6	15	120334	2.3×10^{-5}	1:59	99.16	NSyn, NF, B
14820	7.6	16.6	121584	4.5×10^{-5}	1:01	98.36	NSyn, NF, B
14821	7.6	16.4	30	6.1×10^{-9}	1:51	99.09	
14822	7.5	16.6	120216	1.8×10^{-5}	2:35	99.35	NSyn, NF, B
14823	7.6	17	97827	1.9×10^{-5}	1:57	99.14	NSyn, NF
14824	7.3	17.8	33	1.0×10^{-8}	1:14	98.64	
14825	7.5	16.8	124936	2.2×10^{-5}	2:08	99.22	NSyn, NF, B
14826	7.8	15.9	116380	3.0×10^{-5}	1:27	98.85	NSyn, NF, B
14827	7.5	17.3	37	6.4×10^{-9}	2:11	99.23	
14828	7.6	15.9	34	5.7×10^{-9}	2:16	99.26	
14829	7.3	17	120467	3.1×10^{-5}	1:27	8.85	NSyn, NF, B
14830	7.8	15.4	33	6.3×10^{-9}	1:59	99.16	
14831	7.8	15.5	40	1.5×10^{-8}	1:01	98.36	
14832	7.6	17.3	27	1.7×10^{-9}	1:19	98.73	
14833	7.6	16.8	115875	2.4×10^{-5}	1:48	99.07	
14834	7.6	15.5	33	9.3×10^{-9}	1:20	98.75	
14835	7.6	16.7	31	9.2×10^{-9}	1:16	98.68	
14836	7.5	16.6	27	8.4×10^{-9}	1:13	98.63	

Table 2 (cont'd). FD-565 fiber-optic system test results
(d) Configuration 4

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14837	7.6	16.8	107869	2.3×10^{-5}	1:45	99.05	NSyn, NF
14838	8	14	100561	3.2×10^{-5}	1:10	98.57	NSyn, NF
14839	7.6	15.2	104580	3.0×10^{-5}	1:20	98.75	NSyn, NF
14840	7.8	16.9	100335	1.9×10^{-5}	2:01	99.17	NSyn, NF
14841	7.8	15.7	46	4.2×10^{-9}	4:09	99.59	
14842	7.8	16	50	1.9×10^{-8}	0:59	98.31	
14843	7.6	15.7	97405	2.1×10^{-5}	1:46	99.06	NSyn, NF
14844	7.5	16.4	59	6.0×10^{-9}	3:42	99.54	
14845	7.5	17.4	103315	4.0×10^{-5}	0:58	98.27	NSyn, NF
14846	7.6	16.4	132099	1.4×10^{-5}	3:41	99.55	NSyn, NF
14847	7.6	16	95042	1.6×10^{-5}	2:12	99.24	NSyn, NF
14848	7.5	17.9	56	7.1×10^{-9}	2:58	99.44	
14849	7.6	16.1	98671	3.5×10^{-5}	1:03	98.4	NSyn, NF
14850	7.5	17.4	59	1.0×10^{-8}	2:13	98.25	
14851	7.5	17.4	129666	3.8×10^{-5}	1:17	98.7	NSyn, NF
14852	7.5	16.4	51	1.4×10^{-8}	1:20	98.75	
14853	7.5	16.4	128188	2.7×10^{-5}	1:56	99.1	NSyn, NF, B
14854	7.6	15.6	125037	2.7×10^{-5}	1:44	99.04	NSyn, NF, B
14855	7.6	16.1	99869	2.4×10^{-5}	1:36	98.95	NSyn, NF
14856	7.3	17.4	56	1.7×10^{-8}	1:16	98.68	
14857	7.6	17.3	112324	1.1×10^{-5}	3:48	99.56	NSyn, NF, B
14858	7.8	18.2	52	1.0×10^{-8}	1:56	99.14	
14859	7.5	17.5	100623	3.1×10^{-5}	1:14	98.65	NSyn, NF
14860	7.5	17.7	57	1.5×10^{-8}	1:28	98.86	
14861	7.5	17.4	111861	3.1×10^{-5}	1:21	98.77	NSyn, NF, B
14862	7.6	17.4	59	8.8×10^{-9}	2:32	99.34	
14863	7.5	17.4	103120	2.7×10^{-5}	1:25	98.82	NSyn, NF
14864	7.6	17.2	107990	9.7×10^{-6}	4:11	99.6	NSyn, NF, B
14865	7.6	17.7	49	7.8×10^{-9}	2:22	99.3	
14866	7.6	16.5	119393	2.0×10^{-5}	2:13	99.24	NSyn, NF, B
14867	7.5	17.3	113599	2.4×10^{-5}	1:48	99.07	NSyn, NF, B
14868	7.5	18	106648	1.3×10^{-5}	3:55	99.57	NSyn, NF, B
14869	7.5	17.7	45	1.5×10^{-8}	1:06	98.48	
14870	7.5	17.4	41	7.3×10^{-9}	2:07	99.21	
14871	7.6	17.2	43	9.2×10^{-9}	1:46	99.05	
14872	7.5	17.2	45	6.0×10^{-7}	2:38	99.36	
14873	7.6	17.2	107889	2.3×10^{-5}	1:45	99.04	NSyn, NF, B
14874	7.3	17.3	42	1.1×10^{-8}	1:23	98.79	
14876	7.6	16.5	47	4.2×10^{-9}	4:12	99.6	
14877	7.8	17.2	55	1.9×10^{-8}	1:05	98.46	
14878	7.6	17.5	111573	9.6×10^{-6}	4:24	99.62	NSyn, NF, B
14879	7.5	16.8	44	1.7×10^{-8}	0:59	98.3	
14880	7.8	15.6	1	1.1×10^{-8}	1:02	98.38	
14881	7.8	15.6	32	6.0×10^{-9}	2:01	99.17	
14882	7.6	16	102427	1.8×10^{-5}	2:11	99.23	NSyn, NF
14883	7.6	17.5	40	9.7×10^{-9}	1:33	98.92	
14884	7.5	17.3	40	7.2×10^{-9}	2:05	99.2	

Table 2 (cont'd). FD-565 fiber-optic system test results
(d) Configuration 4 (cont'd)

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14885	7.6	16.1	42	8.8×10^{-9}	1:48	99.07	
14886	7.6	17.2	43	9.3×10^{-9}	1:45	99.04	
14887	7.5	17.7	103668	2.3×10^{-5}	1:44	99.04	NSyn, NF
14888	7.3	17.3	102445	1.8×10^{-5}	2:08	99.02	NSyn, NF
14889	7.5	17.3	33	6.0×10^{-9}	2:04	99.19	
14890	7.	17.8	99205	1.5×10^{-5}	2:26	99.32	NSyn, NF
14891	7.5	17.3	34	6.9×10^{-9}	1:52	99.11	
14892	7.6	16.9	104079	2.0×10^{-3}	1:54	99.12	NSyn, NF
14893	7.5	17.5	45	9.1×10^{-9}	1:52	99.11	
14894	7.5	17.5	42	1.3×10^{-8}	1:15	98.66	
14895	7.5	17.8	104409	2.0×10^{-5}	2:00	99.16	NSyn, NF
14896	7.6	17.7	100335	2.2×10^{-5}	1:45	99.05	NSyn, NF
14897	7.5	17.3	104005	2.0×10^{-5}	1:58	99.15	NSyn, NF
14898	7.5	17.5	39	8.1×10^{-9}	1:49	99.08	
14899	7.3	17.3	40	8.0×10^{-9}	1:53	99.12	
14900	7.5	17.4	41	7.7×10^{-9}	2:01	99.17	
14901	7.6	17.2	101444	1.8×10^{-5}	2:08	99.21	NSyn, NF
14902	7.5	17.9	100469	2.1×10^{-5}	1:47	99.06	NSyn, NF
14903	7.5	17.3	103641	2.0×10^{-5}	1:57	99.14	NSyn, NF
14904	7.6	17	104016	2.2×10^{-5}	1:49	99.08	NSyn, NF
14905	7.6	17	97673	3.7×10^{-5}	1:00	98.33	NSyn, NF
14906	7.6	17.2	106065	2.4×10^{-5}	1:41	99.01	NSyn, NF
14907	7.6	16.8	38	9.7×10^{-9}	1:29	98.87	
14908	7.5	17.8	97095	2.6×10^{-5}	1:23	98.79	NSyn, NF
14909	7.6	17.2	103737	2.5×10^{-5}	1:34	98.93	NSyn, NF
14910	7.5	17.3	39	9.8×10^{-9}	1:30	98.88	
14911	7.6	17.3	101129	1.8×10^{-5}	2:10	98.46	NSyn, NF
14912	7.5	17.5	107813	3.0×10^{-5}	1:22	98.78	NSyn, NF
14913	7.5	17.2	100280	1.8×10^{-5}	2:04	99.19	NSyn, NF
14914	7.6	17.5	33	6.3×10^{-9}	1:59	99.16	
14915	7.6	17.2	42	8.5×10^{-9}	1:52	99.1	
14916	7.5	17.5	103483	2.7×10^{-5}	1:26	98.84	NSyn, NF
14918	7.8	17	105709	2.6×10^{-5}	1:32	98.91	NSyn, NF
14919	7.6	17.7	36	1.0×10^{-8}	1:18	98.71	
14920	7.6	17.9	32	5.2×10^{-9}	2:20	99.28	
14921	7.6	16.4	35	2.3×10^{-9}	5:39	99.71	
14922	7.6	16.5	36	5.9×10^{-9}	1:58	99.15	
14923	7.6	16.8	41	7.9×10^{-9}	1:58	99.15	
14924	7.8	16.8	125617	2.4×10^{-5}	1:56	99.13	NSyn, NF, B
14925	7.6	16.8	127275	2.7×10^{-5}	1:47	99.06	NSyn, NF, B
14926	7.8	17.2	42	1.6×10^{-8}	1:01	98.36	
14927	7.6	16.6	128235	3.7×10^{-5}	1:18	98.71	NSyn, NF, B
14928	7.6	17	121722	4.2×10^{-5}	1:06	98.48	NSyn, NF, B
14929	7.5	17.7	37	9.1×10^{-9}	1:32	98.91	
14930	7.8	17.2	123880	2.2×10^{-5}	2:06	99.2	NSyn, NF, B
14931	7.8	17.7	41	7.8×10^{-9}	1:59	99.16	

Table 2 (cont'd). FD-565 fiber-optic system test results
(d) Configuration 4 (cont'd)

Shot No.	Risetime (ns)	Peak electric field (V/m)	Total errors	Average error rate	Test interval	Percentage of error-free seconds	Comments
14932	7.8	17.2	44	9.0×10^{-9}	1:57	99.1	
14933	7.8	18.3	39	7.7×10^{-9}	1:54	99.12	
14934	7.5	17.8	95256	3.9×10^{-6}	4:03	99.58	NSyn, NF
14935	7.8	16.6	126559	4.8×10^{-5}	1:00	98.33	NSyn, NF, B
14936	7.8	17.7	46	1.0×10^{-8}	1:44	99.04	
14937	7.6	16.5	127560	2.7×10^{-5}	1:48	99.07	NSyn, NF, B
14938	7.8	17	41	1.1×10^{-8}	1:28	98.86	
14940	7.6	16.5	35	1.1×10^{-8}	1:13	98.63	
14941	7.8	17	38	8.0×10^{-9}	1:48	99.07	
14942	7.6	17.4	100176	2.4×10^{-5}	1:35	98.95	NSyn, NF
14943	7.5	17.7	42	1.1×10^{-8}	1:26	98.84	
14944	7.6	17.3	128355	3.8×10^{-5}	1:16	98.68	NSyn, NF, B
14945	7.5	17.5	99307	2.8×10^{-5}	1:21	98.71	NSyn, NF
14946	7.5	16.6	47	1.7×10^{-8}	1:04	98.44	
14947	7.6	17	124605	2.8×10^{-5}	1:39	98.99	NSyn, NF, B
14948	7.8	16.6	37	7.7×10^{-9}	1:48	99.07	
14949	7.6	17	36	8.7×10^{-9}	1:34	98.93	
14950	7.6	17.4	36	1.1×10^{-8}	1:15	98.66	
14951	7.6	17.4	31	7.9×10^{-9}	1:25	98.87	
14952	7.6	16.6	48	2.2×10^{-8}	0:50	98	
14953	7.6	17.2	32	5.1×10^{-9}	2:21	99.29	
14954	7.8	16.9	128115	2.6×10^{-5}	1:52	99.11	NSyn, NF, B
14955	7.6	17	122702	4.5×10^{-5}	1:02	98.38	NSyn, NF, B
14956	7.6	17	38	9.2×10^{-9}	1:33	98.92	
14957	7.6	17.2	45	1.1×10^{-9}	4:07	99.51	
14958	7.6	17	44	1.6×10^{-8}	1:03	98.41	
14959	7.6	16.5	42	1.7×10^{-8}	0:57	98.24	
14960	7.6	17.3	7	3.6×10^{-9}	3:54	99.57	

8. Conclusions and Recommendations

The initial test objectives were to obtain the occurrences of damage, nonrecoverable upset, automatically recoverable upset, or no effect (in a descending order of severity) over a test interval of a minimum of 200 pulses at field levels from 10 to 60 kV/m.

The maximum level of a 60-kV/m free field was not achievable at the simulator facility used. A total of 201 pulses were obtained, approximately two thirds of which were at 43 kV/m, the maximum free-field level attainable with this simulator. In every case, automatically recoverable upset was the only effect. Protection switching at either high or low speed did not take place and signal transmission was lost or upset for at most 3 ms—130 kb in error at a data rate of 44.736 Mb/s.

Two tasks remain to complete the operational test of this optical fiber communication terminal. The first is to expose the system to free-field pulses at levels up to 60 kV/m. This will take place as an adjunct to the AT&T series G optical fiber transmission system test. This test will be done in one of two ways: (1) elevating the test object at the Patuxent River simulator to reduce the distance from the simulator to the test object, thereby increasing the field level to which the test object is exposed; or (2) conducting the test at a facility that has the capability of reaching free-field levels of 60 kV/m at the test object location on the ground. Both of these options are under consideration.

The second task to be completed is the direct pulse current injection of the metallic cable shield and the terminal frame at current levels up to an order of magnitude higher than those coupled to the system during the configuration 4 test reported herein. This test would simulate the case where the cable shield is grounded directly to the frame rather than in an entry vault. This task is a laboratory test and will be conducted before the next free-field simulation test.

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